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Fractured basement play development on the UK and Norwegian rifted margins

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Abstract: Fractured crystalline basement reservoirs (basement) on the UK Continental Shelf (UKCS) and the Norwegian Continental Shelf (NCS) have been underexplored. Over the last 12 years, Hurricane Energy has deliberately set out to explore basement potential by exploring and appraising the Rona Ridge, West of Shetland; and the Rona Ridge Lancaster Field is now being progressed towards being the first UK basement field development. The Norwegian basement play is also recognized as a potentially material resource through serendipitous oil discoveries, with the 16/1-15 well, drilled in 2011, being the first successful full-scale basement test on the NCS. Building on this success, the 2018 Rolvsnes appraisal well (16/1-28 S) has demonstrated the significant basement potential of the extensive Utsira High and confirmed the materiality of a Norwegian basement play. The Rona Ridge and Utsira basement discoveries are used as a comparison with two other, yet to be evaluated, prospective basement plays on the NCS, with the objective of establishing technical subject areas where future UKCS and NCS collaboration would aid in accelerating understanding of the UKCS–NCS basement play.

In this paper, the term ‘basement play’ refers to a petroleum play in which the reservoir is a crystalline crustal rock with an igneous protolith that hosts a natural network of hydraulically conductive fractures. The igneous precursor may or may not have experienced episodes of regional metamorphism up to granulite facies prior to fracturing. The fracture networks have then developed through a variety of deformational and diagenetic processes including cooling, faulting, hydrothermal fluid ingress and fissure development associated with rifting and near-surface diagenetic processes including fragmentation corrosion and dissolution.

Basement plays have long been developed and successfully produced around the world (P’an 1982; Koning 2003; Schutter 2003; Gutmanis 2009; Cuong & Warren 2009). Globally, there are currently 126 fields producing from basement reservoirs in 24 countries, with additional potential in six countries which have yet to develop basement reservoirs, including the UK (McKechnie 2017). Known viable basement plays include the Zeit Bay (Egypt), Bach Ho (Vietnam), La Paz (South America) and

Dongshengpu (China) fields. In the UK, significant, but serendipitous, discoveries of basement oil include the Clair and Lancaster fields along the Rona Ridge, West of Shetland (Fig. 1), and the Cairngorm discovery in the North Sea (Fig. 2). In each of these examples, the basement oil was encountered at depths below the initial exploration target, with a combination of core and well testing providing confirmation of oil presence.

Until recently, basement plays have received little evaluation or investment in the UK and Norway, meaning that any long-term commercial production potential remains uncertain. In this paper, we review known basement plays in the UK Continental Shelf and the Norwegian Continental Shelf (UKCS and NCS, respectively) before going on to examine and compare/contrast their known geological characteristics and evolution through time. We then discuss how near-surface tectonic fissuring processes due to tensile fracture, associated hydrothermal mineralization and weathering are key controls on the porosity and permeability development of basement reservoirs. Finally, we discuss a number of ongoing

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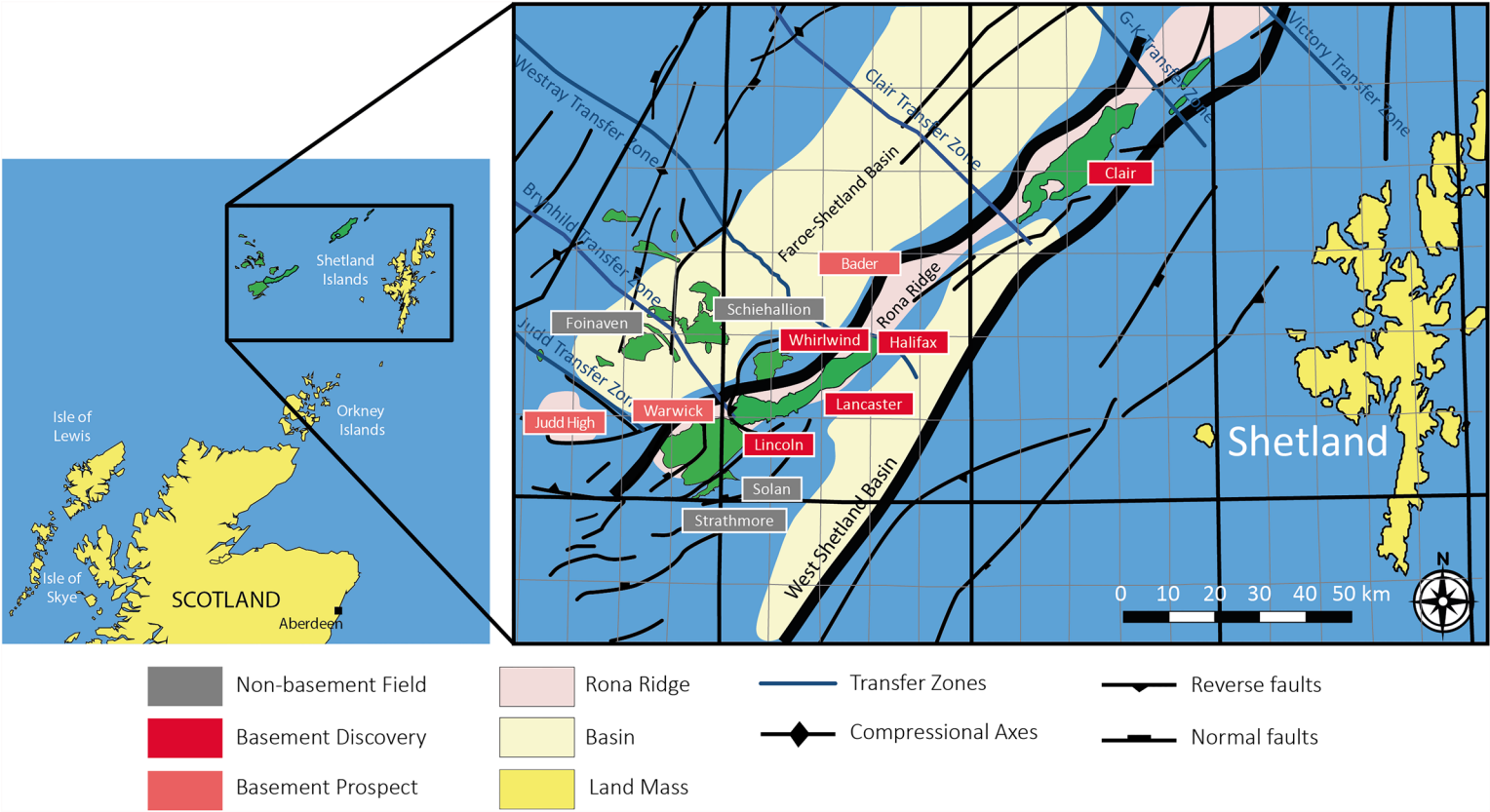


Fig. 1. Basement discoveries and prospects associated with the Rona Ridge. Note that whilst the Clair Field development is of Devonian–Carboniferous sandstones, mobile oil in the underlying Lewisian Basement has been demonstrated via drill stem testing.

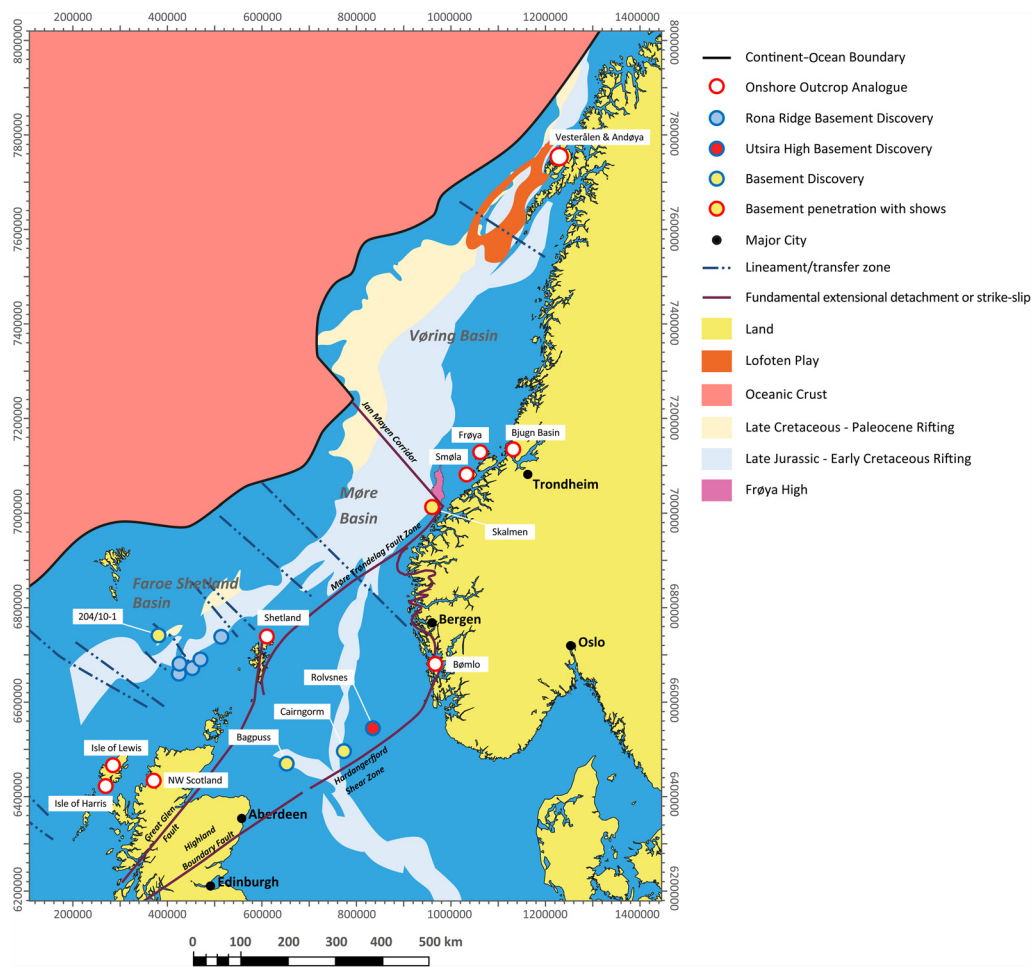


Fig. 2. UKCS and NCS basement plays, discoveries and outcrop analogues referred to in this paper (modified from Faleide *et al.* 2010 and Fossen 2010).

problems encountered during the earlier appraisal and development of basement plays in the UK and Norway, and suggest that knowledge sharing will be a key strategy in the successful opening up of these fascinating geological plays.

Known UK–Norway basement plays

The first UK exploration well specifically designed to target basement play potential was drilled in 2009 – the Lancaster 205/21a-4 exploration well (Trice 2014); this was followed in Norway in 2011 with the 16/1-15 Tellus discovery. Further to four additional wells at Lancaster, a final investment decision has been taken to provide for the first phase of a field development. This first phase comprises two

1 km-long horizontal wells tied back to a floating offtake and production vessel with the intention of producing 20 000 bopd (barrels of oil per day). The first development phase is designed to gather sufficient reservoir information to allow for an optimized full-field development at Lancaster.

Northeastwards along the Rona Ridge, the well-established Clair Field (Fig. 1) comprises fractured Devonian–Carboniferous sandstones overlying a ridge of fractured basement of the Lewisian Gneiss Complex (Ritchie *et al.* 2011). The Clair Field development has focused on resources within the sandstone reservoir; however, resource estimates for the Clair basement potential are currently not published. Despite this focus, basement prospectivity at Clair has been demonstrated from hydrocarbon shows in cuttings, fractured core and drill stem tests (DSTs)

in wells 206/7-1 and 2067a-2 (Elf 1978, 1992; Coney *et al.* 1993). Well 206/7-1 is a vertical hole that penetrated oil-bearing fractured basement. The well was tested over the basement interval, producing 963 bopd, which combined with oil shows indicates a that an oil column of at least 200 m can be interpreted within the basement. 206/7a-2, a horizontal well, penetrated 530 m of basement. The basement was characterized as fractured with specific fracture intervals showing a good correlation to producing zones identified from production log interpretation (Falt *et al.* 1992). After acidification, production rates from the basement were reported at 2110 bopd from an interval with five fracture zones.

The Rona Ridge basement play has been further evaluated through exploration wells at Lincoln, Halifax and Whirlwind (Fig. 1). Utilizing industry standard PRMS Guidelines (2007 SPE/WPC/AAPG/SPEE Petroleum Resource Management System) the resources associated with these discoveries include combined 2P reserves and 2C resources of 2.6 Bbbl (billion barrels) (RPS 2017a, b). An undrilled basement prospect at Warwick (Fig. 1) provides a further potential best-case prospective resource of 935 MMbbl (million barrels) recoverable (RPS 2017b).

Additional West of Shetland basement prospectivity is identified on the Corona Ridge from cored basement acquired below the Eocene Hildasay clastic reservoir in discovery well 204/10-1 (Fig. 2). The Hildasay reservoir forms the development target for the Cambo Field (Fielding *et al.* 2014; Siccar Point Energy 2018). Basement oil has also been identified from the Judd Platform area, where basement oil has been recorded from cores in wells 204/23-1, 204/22-1 and 204/28-1. Undrilled basement prospectivity has also been proposed at the Rona Ridge Bader Prospect (Fig. 1) (Spark Exploration 2018). Basement structures with discovered oil in the UK North Sea include Cairngorm and Bagpuss (Fig. 2). Cairngorm benefits from two basement penetrations, and has been relinquished after well testing and volumetric review (EnQuest 2016). Bagpuss was evaluated by well 13/25, which terminated in granitic basement (Premier 2016). The south Danish Sector of the South Viking Graben also offers basement potential with the undrilled Jarnsaxa prospect (Arden 2018). The Jarnsaxa structure is described as a complex thrust-faulted anticline cut by later faulting episodes, with the reservoir comprising faulted and fractured basement.

On the NCS, the Utsira High (Fig. 2) has been the subject of a focused basement exploration and appraisal programme, culminating in the Rolvsnes horizontal appraisal well 16/1-28S that has demonstrated constrained flow rates of 7000 bopd from fractured and weathered basement with connectivity

to a significant oil volume. Should this well be tied back to the Edvard Grieg Platform, it could provide long-term testing ahead of a development decision to expand productivity by including reserves from the basement (Gaffney Cline 2018). Another prospective basement play is located on the Frøya High, where hydrocarbon prospectivity has been demonstrated by oil shows in the nearby 6306/10-1 well, drilled on the 'Skalmen' prospect (Fig. 2). This well has oil shows in the basement but, despite drill stem testing, no basement oil was brought to the surface. Another prospective basement play offshore of the Lofoten Islands has been identified (see <http://npd.no/en/topics/geology/geological-plays/norwegian-sea/basement/>; the Lofoten play: Fig. 2). Further information on Norwegian basement penetrations are summarized in Slagstad *et al.* (2011), and can also be found in the Norwegian Petroleum Directorate (NPD) Fact Pages (<http://npd.no>).

Despite the prospectivity of basement plays, neither the resource potential nor the mapped extent for the UKCS or NCS has been published. Given the current paucity of public data available, it is challenging to attempt a cross-border comparison. We attempt to do this by subdividing the basement plays into four types: (a) the Rona Ridge basement play ('Rona'); (b) the Utsira High basement play ('Utsira'); (c) the Frøya High basement play ('Frøya'); and (d) the Lofoten basement play ('Lofoten'). This subdivision is based on geographical and geological characteristics. One feature that they share in common is that each play is associated with a notable gravity high, or pronounced gravity lineament, when viewed on the regional gravity map for the North Atlantic and Northern North Sea regions (Fig. 3).

The general characteristics of each basement play and onshore analogues

The Rona play is located on the Atlantic margin, West of Shetland, and comprises a narrow (<15 km wide) upfaulted elongated ridge c. 200 km long of naturally fractured Neoproterozoic granitic-tonalitic orthogneisses, which are likely to be related to the Lewisian Gneiss Complex in NW Scotland (Ritchie *et al.* 2011; Holdsworth *et al.* 2018, 2019). The basement ridge is overlain by a diverse Paleozoic–Cenozoic sedimentary succession (Brooks *et al.* 2001, Ritchie *et al.* 2011), as summarized in Figure 4a. The primary source rock is Kimmeridge Clay, located within the Faroe–Shetland Basin (Fig. 1). The seal is provided by Late Cretaceous mudstones that blanket the ridge following its rapid subsidence below sea level at this time. Rona has been evaluated by drilling and drill stem testing,

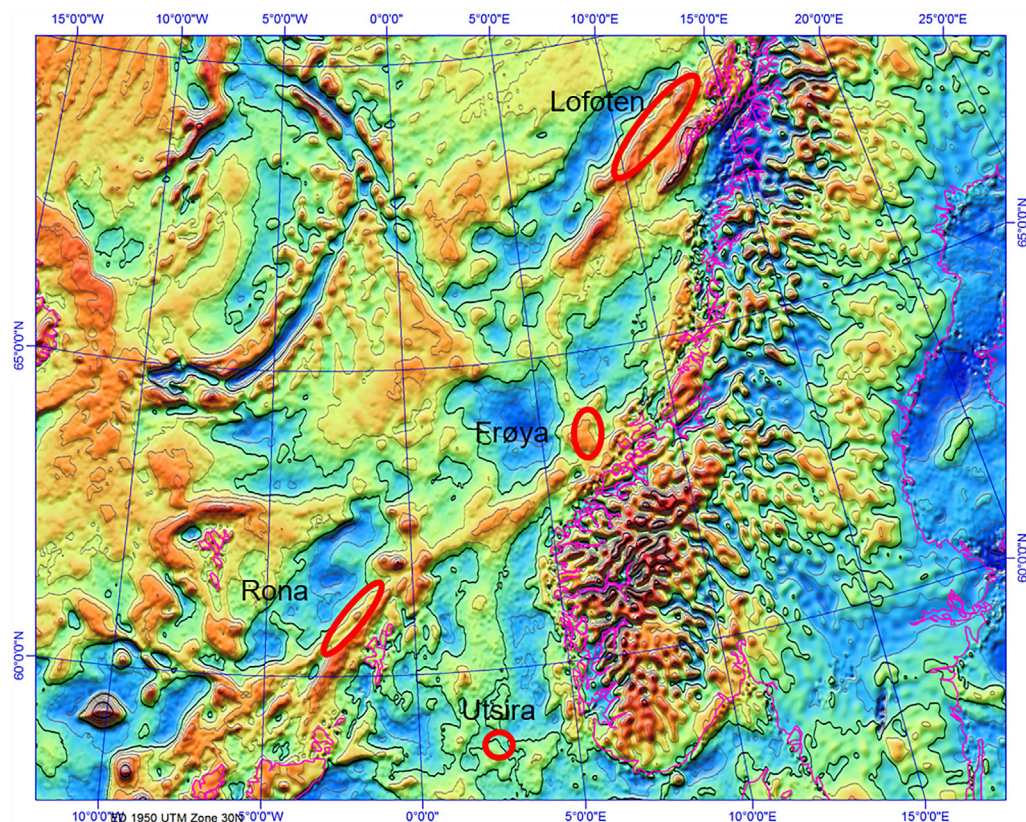


Fig. 3. Gravity map over the North Atlantic and Northern North Sea. The Rona Ridge, Frøya High and Lofoten are all very prominent positive gravity highs, whereas Utsira is much less pronounced. Note how the Rona Ridge and the Frøya High are sitting along the same trend at the margin of the North Atlantic. Gravity map source: https://topex.ucsd.edu/marine_grav/mar_grav.html

and is classified as a Type I naturally fractured reservoir (using the scheme of Nelson 2001; Trice 2014; Belaidi *et al.* 2016) (Fig. 5) as effective porosity and permeability is provided entirely by natural fractures. Outcrop analogues to Rona are found on the west coast of mainland Scotland and the Outer Hebrides (Fig. 2) (Pless 2012; Franklin 2013; Pless *et al.* 2015).

The Utsira play (Figs 2 & 4b) is located in the Norwegian North Sea, and comprises naturally fractured and locally heavily weathered Caledonian basement comprising granite and granodiorite of mid-Silurian–early Devonian age. The basement is sufficiently weathered so that it can be locally classified as a saprolite (Fig. 6). It is overlain by Mesozoic and Cenozoic successions (Fig. 4b). The Late Jurassic Kimmeridge Clay is the main source rock. This is mature in the basalinal areas to the west (Viking Graben), and relatively long-distance migration is required to charge across the Utsira High basement high. The burial of the Utsira High is diachronous;

in the southern parts, Early Cretaceous shales drape the high and act as a regional seal. Towards the north, the regional seal is younging and can be as young as Late Cretaceous chalk (Copestake *et al.* 2003). In addition to fracture porosity, the unweathered basement exhibits intragranular and intercrystalline porosity (Riber *et al.* 2015, 2017; Lie *et al.* 2016) and can therefore be classified as a Type I–II fractured reservoir. Outcrop analogues of the basement are found on the west coast of Norway on the island of Bømlo (Fig. 2).

The Frøya play sits along the North Atlantic margin, just north of the Møre–Trøndelag Fault Complex (MTFC) and within the Jan Mayen Fracture Corridor (JMFC) (Gernigon *et al.* 2015) (Fig. 2). The NNE–SSW-orientated Frøya High covers an area of approximately 5000 km² and only four wells have possibly drilled into basement on the high *sensu stricto* (wells 6306/6-1, 6306/6-2, 6407/10-3 and 6407/10-4: <http://www.npd.no>), and only limited core materials exist. The basement comprises

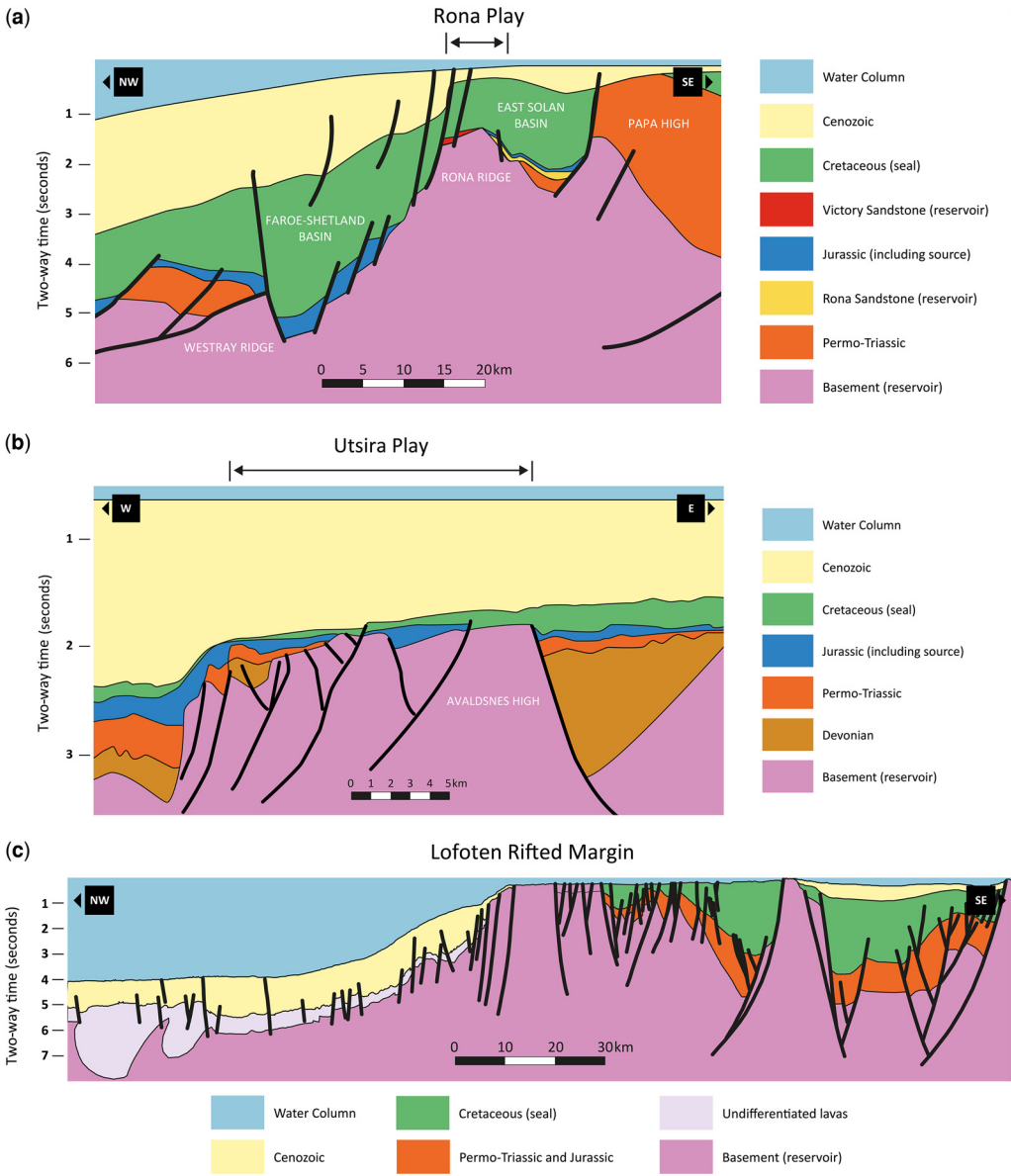


Fig. 4. Representative cross-sections through the basement plays: (a) Rona, (simplified from Brooks *et al.* 2001); (b) Utsira (simplified from Lie *et al.* 2016); and (c) Lofoten (simplified from Faleide *et al.* 2010).

Ordovician granitic intrusives and metamorphic rocks possibly belonging to the Upper or Uppermost Allochthon in the Caledonian tectonostratigraphy (Slagstad *et al.* 2011). It is uncertain how severely weathered and fractured the basement is, although well 6306/10-1 reported large mud losses indicating that it is likely to be heavily fractured. Frøya is thus expected to be classified as a Type I and/or Type II naturally fractured reservoir, depending on future

well positions relative to the high. The source rocks contributing hydrocarbons towards the Frøya High are likely to be of Late Jurassic age, similar to the Kimmeridge Clay in the North Sea. However, Cretaceous source rocks are also likely to be contributing from the deep Rås Basin west of the high (Riis *et al.* 2005) from well-tied seismic interpretation, and Triassic clastics are found directly overlying highly faulted basement in the NE (Fig. 7a). In the

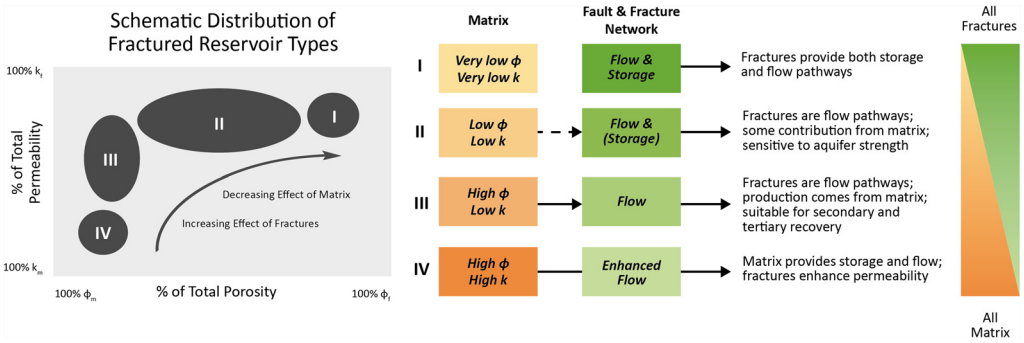


Fig. 5. Fractured reservoir classification and associated reservoir characteristics (modified from Nelson 2001).

central part, basement is in places overlain by onlapping Late Jurassic (?)–Early Cretaceous sandstones, as observed in well 6306/6-2. Broadband reprocessed seismic data show that deep Paleozoic basins (possibly Devonian or Carboniferous) may rest on basement in the southern part of the high (Fig. 7b). Fault interpretation and seismic extractions, along with modern aeromagnetic data, strongly suggest that Frøya is heavily fractured. The entire high has experienced long exposure to weathering processes. However, how much weathered material is preserved is likely to be determined by how severe the Late Jurassic erosion was at any particular location. Due

to the diachronous drowning of the high following this major erosional episode caused by rifting and uplift, mudstones ranging in age from Late Jurassic to Late Cretaceous form a regional seal across the high. Potential outcrop analogues for the Frøya basement are Caledonian Upper or Uppermost Allochthon metamorphic rocks and Ordovician–Silurian intrusives found on the islands offshore Trøndelag. Furthermore, potential analogues for a Devonian succession can be found in the Bjugn Basin and the nearby islands of Smøla and Frøya (Fig. 2).

The NE–SW Lofoten basement play, offshore northern Norway, comprises naturally fractured

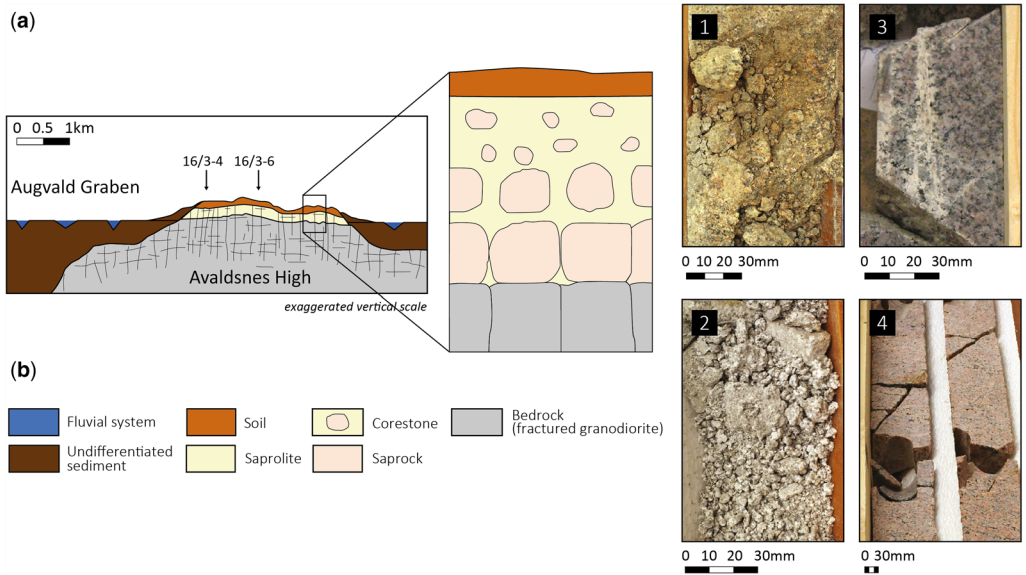


Fig. 6. Conceptual model showing (a) the development of regolith mantle on the Avaldsnes High from pre-Triassic to the Late Jurassic and (b) schematic of regolith mantle lithologies. Core photographs represent typical regolith lithologies: (1) arenitized bedrock; (2) argillized bedrock; (3) bedrock exhibiting disintegration along fractures; and (4) fractured bedrock. Modified after Riber *et al.* (2015, 2017).

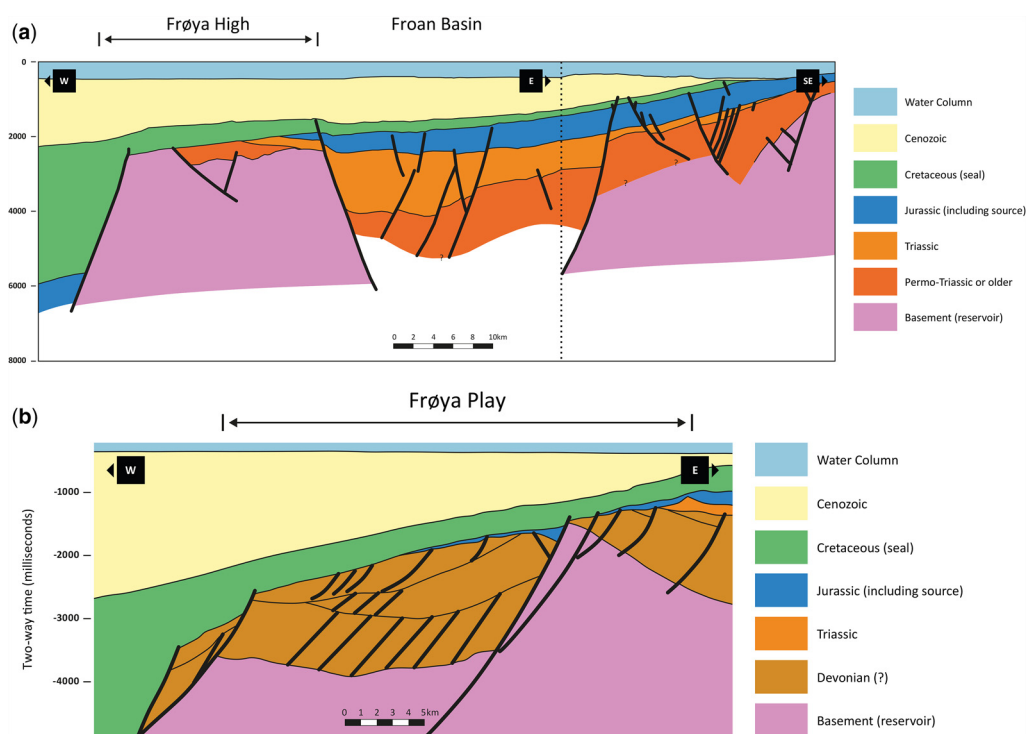


Fig. 7. Representative cross-section through (a) the northern area of the Frøya High (modified from Brekke 2000). The cross-section in (b) the southern Frøya High is based on seismic interpretation only and remains untested by any wells to date. An equally valid model for this cross-section is one where basement sits directly below the Base Cretaceous Unconformity.

Archean orthogneisses (Wilson *et al.* 2006; Bergh *et al.* 2014; Brønner *et al.* 2017), as shown in boreholes from Vesterålen and Andøya (Fig. 2) that include four wells which were cored and logged to evaluate the potential of deep weathering effects on basement (Brønner *et al.* 2017). A cross-section based on publicly available data (Fig. 4c) (Mokhtari & Pegrum 1992) shows Triassic and Jurassic successions directly overlying the basement, with Cretaceous and Cenozoic sediments providing potential seals. The likely source rock for any hydrocarbons here are Late Jurassic mudstones in the adjacent basinal areas. Importantly, breaching the basement of the Cenozoic cover may locally remove trap potential (Fig. 4c). In addition, continued present-day isostatic rebound of the Norwegian mainland as a response to the Plio-Pleistocene glaciations may also be critical factors for hydrocarbon retention in traps in this region (Stoddart *et al.* 2015; Fjeldskaar & Amantov 2018). Outcrop analogues to Lofoten are found on the Vesterålen archipelago, as well as on the island of Andøya (Fig. 2) (Wilson *et al.* 2006). There are insufficient data to unambiguously classify Lofoten as a naturally

fractured reservoir play, but the onshore analogues suggest that it could comprise of basement having both Type I and Type II fractured reservoir characteristics.

Understanding the geology of basement plays in the UKCS and NCS

Basement composition and implications for fracture development

There are notable lithological similarities and differences in the basement across the four plays. The Rona Ridge is the best known part of the Neoproterozoic Faroe–Shetland Terrane located to the north of Scotland and West of Shetland (Fig. 1) (Ritchie *et al.* 2011; Holdsworth *et al.* 2018). Offshore cores and limited onshore outcrops in Shetland reveal a suite of predominantly granodioritic–granitic orthogneisses, including tonalite–trondhjemite–granodiorite (TTG), together with lesser volumes of foliated granitoids and subordinate dioritic–mafic gneisses and amphibolites. One of the longest

and most complete set of cores comes from the Clair Ridge well 206/7a-2 (for a description see [Holds-worth *et al.* 2018](#)). These rocks appear to correlate with the Lewisian Gneiss Complex along strike in NW Scotland, having experienced intense amphibolite-facies metamorphism soon after their intrusion at c. 2.8–2.7 Ga. However, they differ in that they lack the younger Paleoproterozoic reworking events (Inverian, Laxfordian) seen in Scotland and the Outer Hebrides.

Some parts of the Rona Ridge are unusually lithologically uniform and little affected by early ductile deformation. At Lancaster, for example, the lithology is dominated by little-foliated Neoproterozoic tonalitic rocks (90–95% by volume: [Belaidi *et al.* 2016](#)). Their metamorphosed character is only clearly apparent in thin sections, where the ubiquitous development of seriate interlobate to amoeboid textures in plagioclase and quartz point to the operation of grain-boundary migration recrystallization under at least upper-amphibolite facies, as does the presence of orthopyroxene and the widespread development of tapered deformation twins in plagioclase ([Fig. 8a](#)) ([Passchier & Trouw 2005](#)). These textures are very different to the primary igneous textures (e.g. euhedral–subhedral crystal shapes, poikilitic textures, oscillatory zoning) seen in little-deformed, non-metamorphic tonalite plutons such as in the Adamello Massif ([Fig. 8b](#)).

It is anticipated that the Lofoten offshore basement will also be metamorphic and tonalite–granodiorite dominated, as the onshore archipelago is dominated by Neoproterozoic–Paleoproterozoic gneisses and plutons of this composition ([Wilson *et al.* 2006](#); [Bergh *et al.* 2012](#)). The plutons are charnockitic and the preservation of orthopyroxene formed due to the overprinting high-grade metamorphism is in some ways similar to the metatonalites at Lancaster. Younger Caledonian fabrics are only weakly developed here and large regions of gneiss have experienced granulite-facies metamorphism during the Paleoproterozoic ([Corfu 2004](#)).

The Caledonian basement rocks of the Utsira High formed during closure of the Iapetus Ocean and the Silurian–Devonian collision of Baltica and Laurentia ([Roberts 2003](#); [Slagstad *et al.* 2011](#); [Gunterberg 2013](#)). This was associated with subduction-zone development with associated allochthons, including sedimentary and igneous rocks, and island arc complexes. Published data from 18 basement cores acquired from the Utsira High indicate a range of metasandstones, phyllites, granites, granodiorites and gabbroic rocks ([Riber *et al.* 2015](#)), but the dominant lithologies are granite and granodiorite. Associated with the island arc complexes are magmatic intrusive, and the core sample granites from the Utsira High are most similar in composition to the Sunnhordland Batholith and the Krossneset

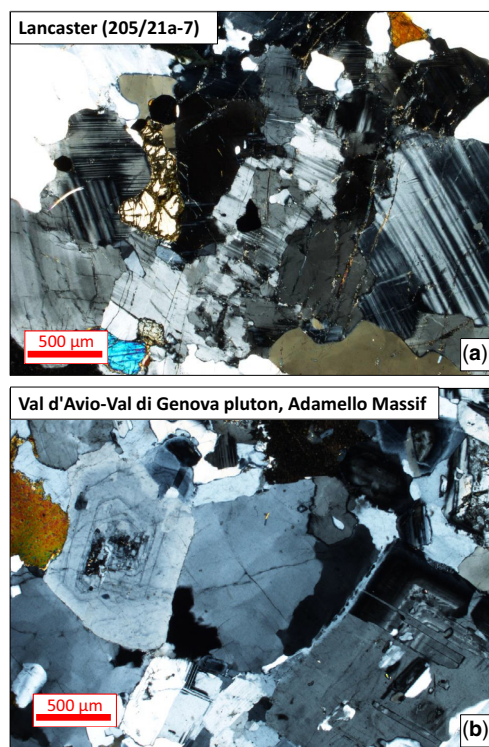


Fig. 8. Thin sections of (a) metatonalite (c. 2.75 Ga) and (b) unmetamorphosed tonalite (c. 30 Ma) from the Lancaster basement and the Adamello Massif, Italy, respectively. Despite the very modest amount of deformation, the metamorphic textures of the Lancaster sample contrast strongly with the obvious primary igneous textures in the Adamello sample. Both images are cross-polar views.

Granite, both of which crop out on the island of Bømlo ([Gunterberg 2013](#)).

The Frøya High has a long, complex evolution closely connected to the tectonic history of the nearby MTFC and the Jan Mayen Corridor ([Fig. 2](#)). From gravimetric and aeromagnetic data, the Frøya High displays a very strong positive anomaly, comparable to the intrusive granites of the Transscandinavian Igneous Belt, a zone of batholiths of Paleoproterozoic age (1.8–1.65 Ga) that were later deformed by the Sveconorwegian Orogeny ([Bingen *et al.* 2008](#)). However, U–Pb zircon dating and the petrology of basement found in wells (e.g. 6407/10-3) suggest intrusive granites of Ordovician age, which are also found in outcrops on nearby islands. This indicates that (at least, in part) the Frøya High basement belongs to the Upper or Uppermost Allochthon in the Caledonian tectonostratigraphy ([Slagstad *et al.* 2011](#)). Like the Clair Field, modern seismic data indicate that there may be deep Paleozoic (possibly

Devonian–Carboniferous) basins located over the southern part of the high (Fig. 7b). The exact age and burial history here are unknown.

Overall, the four basement plays discussed here are granitic in general compositional terms. This is a typical feature of most of the 23 producing basement fields evaluated worldwide. This is significant since lithologies that contain a higher proportion of quartz and feldspar tend to be associated with higher fracture intensities in the upper crust (Stearns 1967; Stearns & Friedman 1972), with open water-filled fissures in crystalline rocks being recorded at more than 12 000 m depth (Stober 1996). The cooling of igneous melts or metamorphic rocks tends to lead to the widespread development of non-strata-bound joint sets (Koenders & Petford 2003). Such joint sets can be deeply penetrating features (Odling *et al.* 1999), and can be readily reactivated and exploited by subsequent deformation, hydrothermal and diagenetic processes. (e.g. see Dempsey *et al.* 2014). Consequently, joint sets associated with crystalline basement reservoirs tend to show depth-consistent frequencies and penetration to several kilometres (Seeburger & Zoback 1982). Fracture systems of this kind are widely developed in the onshore basement correlative rocks in both Shetland and Scotland (Pless 2012; Franklin 2013). Depth-independent joint frequencies are recorded from the Rona Ridge (Trice *et al.* 2018). Based on observations of joint and fracture systems in onshore analogues such as the Vesterålen Andøya archipelago (e.g. Wilson *et al.* 2006), it is likely that the Norwegian basement plays will also have fracture networks dominated by extensive and deep penetrating joints with associated potential fracture permeability extending to depths of at least 1 km and possibly more.

Trap development through time

All four basement play types show similarities in their geological histories during offshore basin development that are apparent from the geological cross-sections (Figs 4 & 7) and their locations relative to major structural lineaments (Figs 2 & 3). All are located proximal to petroleum-generating kitchen (basinal) areas on normal fault-bounded structural highs formed during later Paleozoic–Mesozoic extension (Blystad *et al.* 1995; Ritchie *et al.* 2011; Stoker 2016). The plays are also associated with major regional unconformity surfaces, with the drowning of the basement palaeorelief, which generally occurred in the Cretaceous, blanketing the highs with marine mud rocks leading to ‘buried hill’ trap formation in all plays (Figs 4 & 7). The broad coincidence of Late Cretaceous drowning in the UKCS–NCS region may reflect the regional development of the NE Atlantic margin at this

time, together with the unusually high global sea levels (Haq 2014). Post-burial phases of uplift and inversion are also important processes. The geological development of these traps and potential traps through time is discussed below.

Permo-Triassic rifting, which culminated in the north–south-trending graben geometry of the Northern North Sea and Norwegian North Sea (Evans 2003; Sajjad 2013), was also associated with a warm and dry climate that lasted into the Late Triassic. Throughout this period, peneplanation and associated deep basement weathering (Lidmar-Bergström 1993; Olesen *et al.* 2013) occurred in Norway, as well as over a wide area of Scandinavia (Fredin *et al.* 2017). Triassic exposure and continental weathering products have been inferred to have affected the Rona play through the presence of aphanocrystalline hematite recorded 300 m (true vertical depth) below the basement unconformity (Trice *et al.* 2018), and from the presence and character of Triassic sediments which onlap the northern flank of the Rona Ridge at Lancaster (Fig. 4a). In the onshore Outer Hebrides, early Triassic red beds of the Stornoway Formation (Steel & Wilson 1975; Franklin 2013) are also seen unconformably overlying Lewisian gneisses on the likely southwards continuation of the Rona Ridge.

Extension and associated tensile fault–joint system generation are interpreted to have continued throughout the Triassic and Jurassic rifting (Booth *et al.* 1993). A variety of coarse-grained clastics document the continued subaerial exposure of the basement ridges. Examples include the Jurassic Rona Sandstone which exhibits reworked basement clasts in marine and clastic deposits onlapping the Rona play basement (Fig. 4a), and the Jurassic Draupne Sandstone overlying the Utsira High (Fig. 4b) which contains clasts of granitic and metamorphic rock (Maystrenko *et al.* 2017). There are conglomerates with clasts of metamorphic and granitic basement rocks in the Triassic section that overlies the northern part of the Frøya High (Fig. 7).

At Lofoten, existing seismic profiles show a relatively thin pre-Cretaceous sequence covering the basement on the Lofoten shelf on top of the basement (Mokhtari & Pegrum 1992). The sedimentary basins here are known to contain Triassic, Jurassic and Cretaceous strata. There is evidence from the Ribban Basin, west of the Lofoten Islands, which suggests that the Jurassic sediments consist of shallow-marine sandstone wedges that are interpreted to have filled the accommodation space created during rifting (Okere 2010), followed by an Late Jurassic shale, including a Kimmeridge Clay source-rock equivalent (Fig 2013). Preserved sediments in the northern part of the Ribban Basin show that the regional transgression came from the north, and that large areas of the Lofoten/Vesterålen offshore and onshore areas

were flooded at this time (Løseth & Tveten 1996). This interpretation is reflected in Figure 4c, which shows an undifferentiated Triassic and Jurassic sequence present within the Lofoten basins. However, the basement highs locally have limited Mesozoic and Cenozoic seals adding an additional challenge to defining a mappable basement prospect.

The subaerial exposure of the basement plays terminated in the Cretaceous. At Rona, an Early Cretaceous marine sandstone, the Victory Formation (Goodchild *et al.* 1999), locally onlaps the NW flank of the Rona Ridge. This shallow-marine package contains evidence of reworked basement and is overlain by deeper-water marine clays of the Valhall Formation, which regionally blanket the Rona Ridge as it subsided during North Atlantic margin development. On the Utsira High, the Early Cretaceous Åsgard Formation terminates basement subaerial exposure and heralds the onset of a long period of subsidence throughout the later Mesozoic and Cenozoic. Early–Late Cretaceous sediments onlap the flanks of the Frøya High, but the basement high was not fully covered until the Late Cretaceous following the onset of North Atlantic rifting in the Maastrichtian–Paleocene (Theissen-Krah *et al.* 2017). At Lofoten, Early Cretaceous fault movements uplifted the Lofoten Ridge as a horst, which was subsequently eroded and the surrounding areas of Andøya and Vesterålen subsided below thick Early Cretaceous successions (Hansen *et al.* 2012).

Due to localized crustal compression in parts of the Faroe–Shetland Basin (Stoker *et al.* 2017), Lancaster underwent 1–1.5 km of vertical uplift during the Cenozoic (Fig. 9). Burial history and maturity modelling indicate that this uplift was likely to have been coeval with final hydrocarbon charge. Such an interpretation is consistent with published data that show that the Rona Ridge acted as a focal point for hydrocarbon migration since the Late Cretaceous (Dean *et al.* 1999). Whilst no clear evidence of fracture reactivation has been so far identified from Rona Ridge cores, the authors consider that such uplift would enhance the existing fracture-hosted porosity and permeability through acidic fluids associated with oil migration, resulting in the dissolution of calcite (van Berk *et al.* 2014) and feldspar, and the termination of subsequent mineral infills within the reservoir pore space. The present-day structure at Utsira (Fig. 4b) results from late Plio/Pleistocene subsidence and uplift (Lie *et al.* 2016). The late development of the structure here implies late and ongoing migration of hydrocarbon into the reservoir (Lie *et al.* 2016), and it is probable that the late charge, if coeval with uplift, will have contributed to the preservation of fracture porosity and permeability within Utsira by similar processes to those documented at Rona.

During the Late Cenozoic, there was uplift and erosion of the entire margin along the Norwegian Sea, affecting the Frøya High as well as Lofoten and Vesterålen. This can be demonstrated in the Lofoten region by a late Cenozoic prograding seismic sequence immediately below the base of the Pliocene–Pleistocene glaciomarine sequence (Løseth & Tveten 1996). The Frøya High experienced significant westwards tilting and uplift of the eastern parts from the Mid-Miocene to present day, as evidenced by deep erosion towards coastal areas and the westwards outbuilding of large prograding wedges (Blystad *et al.* 1995). In Lofoten and Vesterålen, this effectively reactivated pre-existing rift systems (Imber *et al.* 2005), and it is probable that this uplift has had a positive impact on the Lofoten play potential by enhancing the fracture network through tensile failure and providing an enhanced porosity and permeability system for any Cenozoic hydrocarbon charge. However, uplift also causes erosion of the overburden, increasing the risk of failure due to breaching of trap, as seen in Figure 4c.

The four plays are located in an area subject to glacial isostatic adjustments associated with the repeat melting and progradation of Quaternary ice sheets (Olesen *et al.* 2013). Such a process could contribute to structural relaxation (Mode I extension) of the existing fault/fracture networks at shallow depths, a process that would be enhanced if coeval with hydrocarbon charge. Ice melting and associated lithospheric unloading is also postulated as having contributed to the hydrocarbon charge in the Utsira High (Stoddart *et al.* 2015).

Fissuring and weathering processes

The common feature of the geological histories of the four basement plays is that they are all subconformity-buried hill traps, the form of which depends on the geometry of the erosional surface and the underlying basement high (Biddle & Wielchowsky 1994). An evaluation of a commercially available oil and gas field database (DAKS™; C&C Reservoirs 2018) shows that buried hill traps are the most common form of trap in global basement plays, with 13 out of the 23 basement fields evaluated being of this type. The nature of the buried hill trap means that the reservoir is affected by subaerial diagenetic processes. During uplift and/or exposure, this can lead to the precipitation and dissolution of mineral cements in fractures, the widening of fractures, and the potential for saprolite development, which can lead to the development of a crust of arenaceous material with enhanced intergranular porosity. Furthermore, weathering preferentially breaks down more unstable ferromagnesian minerals such as amphibole and pyroxene into clay, which can lead to the creation of secondary porosity

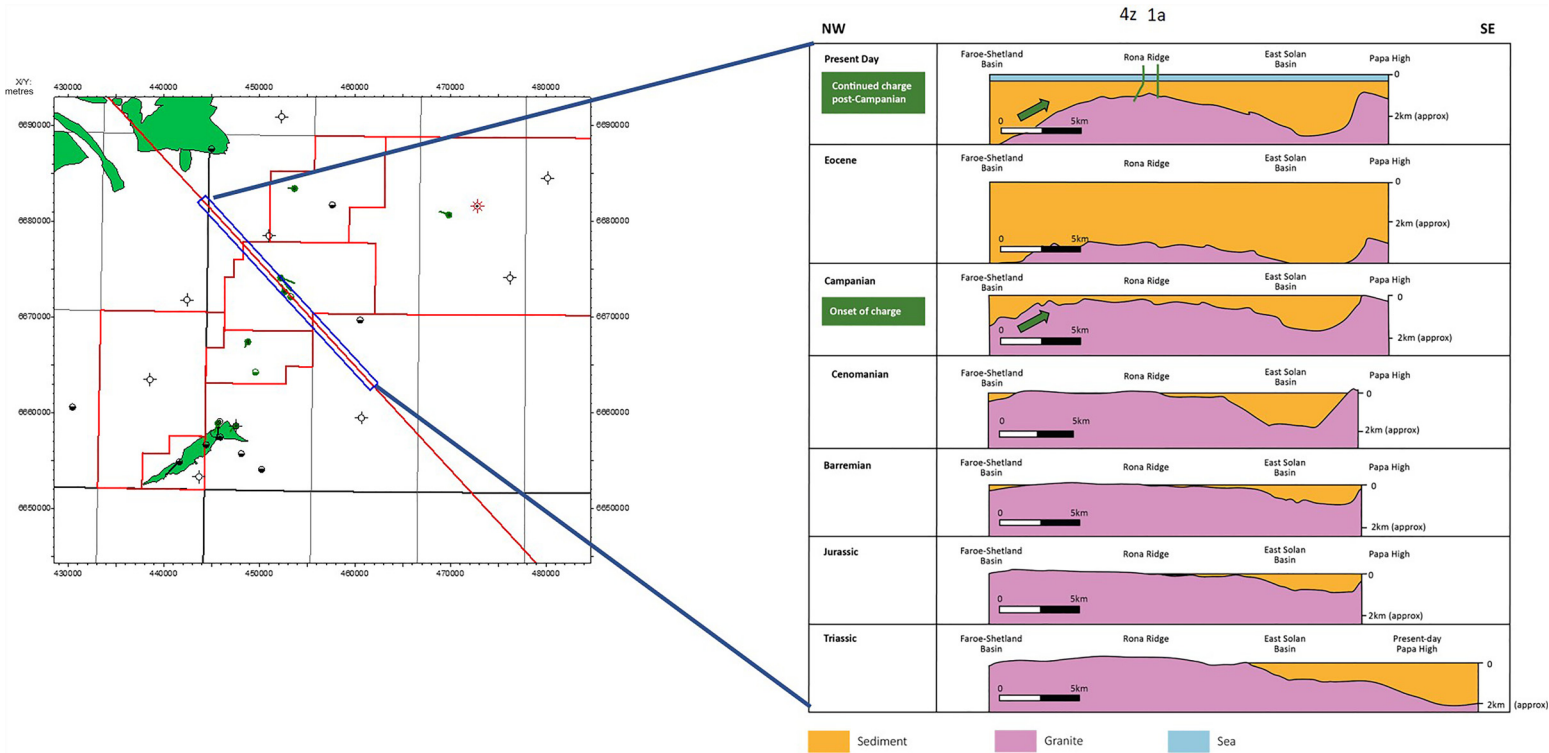


Fig. 9. Sequential interpreted back-stripped seismic cross-sections representing sedimentary onlap onto basement structures at Lancaster. The map insert references the line of cross-section 'centred' on Rona Ridge wells 205/21a-4z and 205/21-1a (Trice *et al.* 2018).

and further fracturing due to volume changes and void collapse. These processes are particularly important when they occur coevally with active rifting, which can lead to deep and pervasive fissuring where active normal faults reach the surface as wide open tensile fissures with well-connected and deeply penetrating void spaces that extend to depths of at least many hundreds of metres (van Gent *et al.* 2010; Holland *et al.* 2011). Such fault systems may also be host to near-surface hydrothermal mineralization and fluid flow related to enhanced heat flow during rifting (Frenzel & Woodcock 2014).

The Rona Ridge basement play is demonstrably affected by Mesozoic extensional faults and fissures, combined with near-surface hydrothermal and weathering processes (Holdsworth *et al.* 2019). At Lancaster and Lincoln, for example, mineralized sediment- and breccia-filled fissures (e.g. Fig. 10b, d) estimated to be up to several metres wide (Belaidi *et al.* 2016) occur deep within the basement high, with cobbles of weathered tonalite and limestone being recovered from fault zones at 400 m (true vertical depth) below the top basement surface (Fig. 10c) (Trice *et al.* 2018). Mineral cements and vein fills include calcite, adularia, quartz-chalcedony, pyrite and zeolite, with zoned cockade-style textures typical of shallow-crustal hydrothermal mineralization in open fracture systems (Fig. 10e) (Frenzel & Woodcock 2014). The sediment/breccia infills and pebbles (Fig. 10c) are interpreted as having been introduced into deeply penetrating open fissures through a combination of surface-water ingress and gravitational processes (Trice *et al.* 2018; Holdsworth *et al.* 2019). In Lincoln, given that the overlying Cretaceous section was isolated by a casing string prior to drilling the basement, it is speculated that a pebble of Aptian limestone entered the palaeofracture network soon after its initial deposition, whilst the Rona Ridge was locally a marine coastline/island setting (Trice *et al.* 2018). A restricted zone of microcracked and altered weathered basement 10–15 m thick occurs at Lancaster (Fig. 10d), but other parts of the basement high, such as the Clair Ridge, are almost totally free of weathered material at the top basement interface (Holdsworth *et al.* 2019).

In stark contrast to Rona, basement saprolites are very well developed across Scandinavia (Gunterberg 2013; Riber *et al.* 2015; Fredin *et al.* 2017), with most of the cores evaluated from the Utsira High showing signs of post-crystallization alteration (Riber *et al.* 2015). Whilst the exact process of diagenetic alterations cannot be established for all well penetrations, it is evident that, from Late Triassic time, the basement was subaerially exposed and deep weathering took place. Weathering profiles have been established from core (Fig. 6) by the

presence and nature of clay minerals (kaolinite, and mixed layer illite and smectite) and upwards-increasing alteration profiles, associated with the basement unconformity surface. The associated decomposition of the host rock leading to arenization and argillization is controlled primarily by feldspar and biotite dissolution, initially by fluid ingress via pre-existing fractures (Riber *et al.* 2015, 2017).

The presence of kaolinite, hematite and loose angular quartz grains in a palaeosol (c. 10 m) and about 20 m of associated underlying (aerial) weathered basement section is reported from well 6306/10-1 located just south of the Frøya High. The basement comprises fractured and altered granitic gneisses of Ordovician age based on U–Pb zircon dating (Slagstad *et al.* 2011). Mineral alteration forming secondary minerals such as chlorite and epidote (replacing biotite and feldspars) and sericite (replacing feldspars) is seen in the basement core taken about 150 m below the base of the (aerially) weathered section (Robertson 1990). K–Ar dating of hornblende in the core yields an Early Carboniferous age (335 ± 2 Ma), which is believed to represent the exhumation age (http://factpages.npd.no/pbl/wellbore_documents/1551_6306_10_1_COMPLETION_REPORT_AND_LOG.pdf Final Well Report; FM Geochronological Report FMK3129, FM Consultants Ltd 1990). The basement is directly overlain by Middle Jurassic Bathonian sedimentary rocks deposited in a shallow-marine environment (http://factpages.npd.no/pbl/wellbore_documents/1551_6306_10_1_COMPLETION_REPORT_AND_LOG.pdf Final Well Report), indicating long exposure of the basement. Although this well is not located on the Frøya High *sensu stricto*, it is considered to be an analogue for the Frøya play in terms of periods of uplift and subaerial exposure prior to the Late Jurassic rifting. It is thus anticipated that aerial weathering, as well as deep leaching causing alteration of minerals, are likely to have taken place across the Frøya High, perhaps for as long a time period as, for example, Late Paleozoic/Early Mesozoic–Late Jurassic, depending on the location.

Outcrops and boreholes indicate that the basement exposed at Vesterålen and Andøya has significantly less saprolite compared to Utsira, but there is a localized potential for deep saprolitic weathering. For example, the southern boundary of the Ramså Basin (located on the NE coast of Andøya Island) shows exposed, deeply weathered basement (Brønner *et al.* 2017).

The significance of subaerial weathering to global basement reservoirs can be seen in Figure 11, which demonstrates porosity ranges from 23 producing basement fields worldwide (data sourced from DAKS™: C&C Reservoirs 2018). It is clear that weathering and hydrothermal alteration are key mechanisms for porosity enhancement in Type I

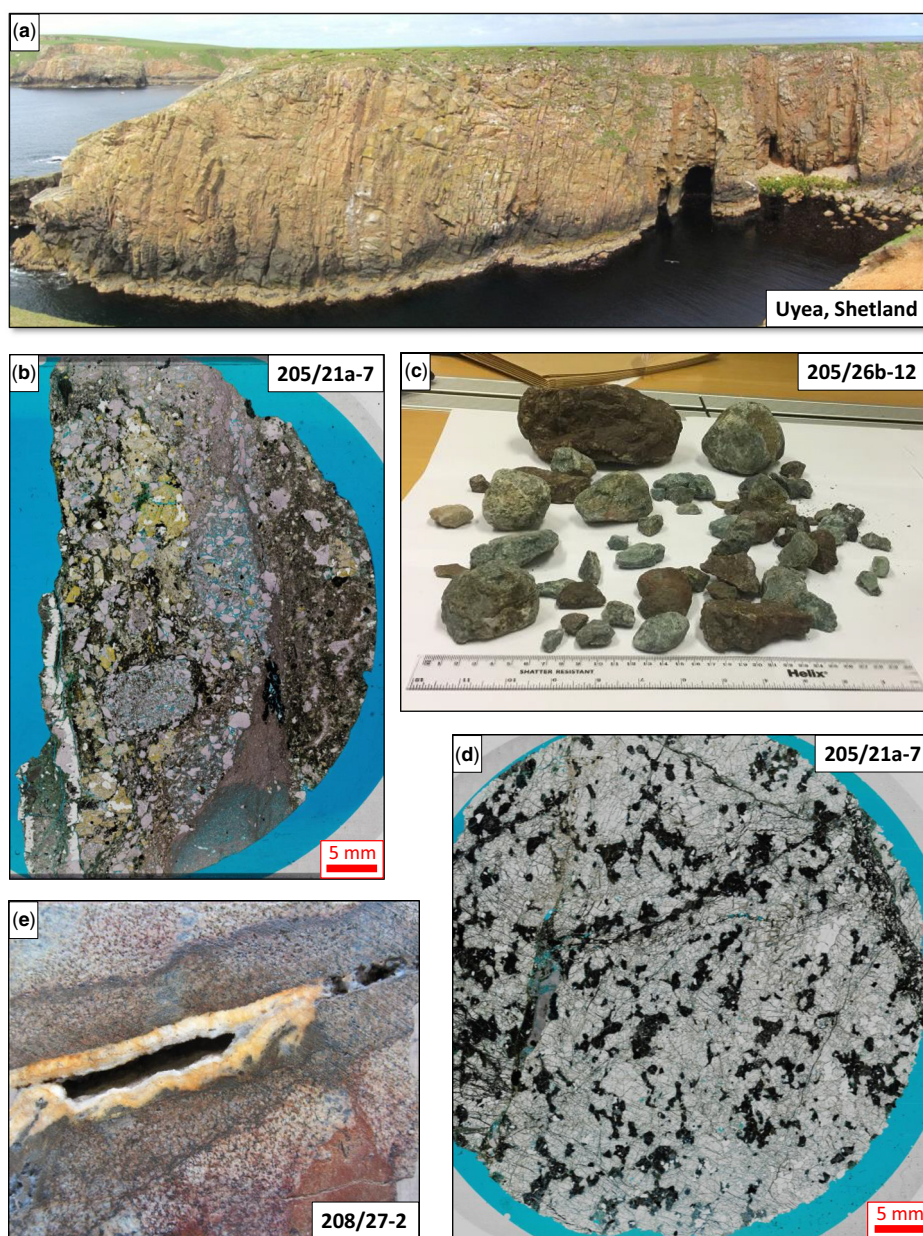


Fig. 10. Typical features seen in basement reservoirs. (a) Deeply penetrating, long planar joints and fractures developed in c. 2.75 Ga orthogneisses thought to be direct onshore equivalents of the Rona Ridge basement in Shetland (for the location see Fig. 2). (b) Typical weakly foliated fissure fill sampled over 150 m below the top basement unconformity at Lancaster. Most, but not all, of the clasts are locally derived, but are more altered and, together with the widespread development of calcite and silica cements, residual oil stains and preserved porosities up to 10% or more point to a long history of focused fluid flow. Scale bar 2 mm. (c) A selection of pebbles sampled from fissures in the Lincoln basement. (d) Thin section of weathered basement from Lancaster showing pervasive microcracking and alteration of mafic minerals to dark clay minerals. PPL view. Note secondary porosity development and small fissure fill on the right hand side of the image. The scale bar is 2 mm. (e) Hydrothermal calcite and quartz mineralization coats a large fracture-hosted vuggy cavity that was filled with oil (note the oil stain) from basement at the northern end of the Rona Ridge. The fracture (including mineral fill) is 15 mm across at its maximum width.

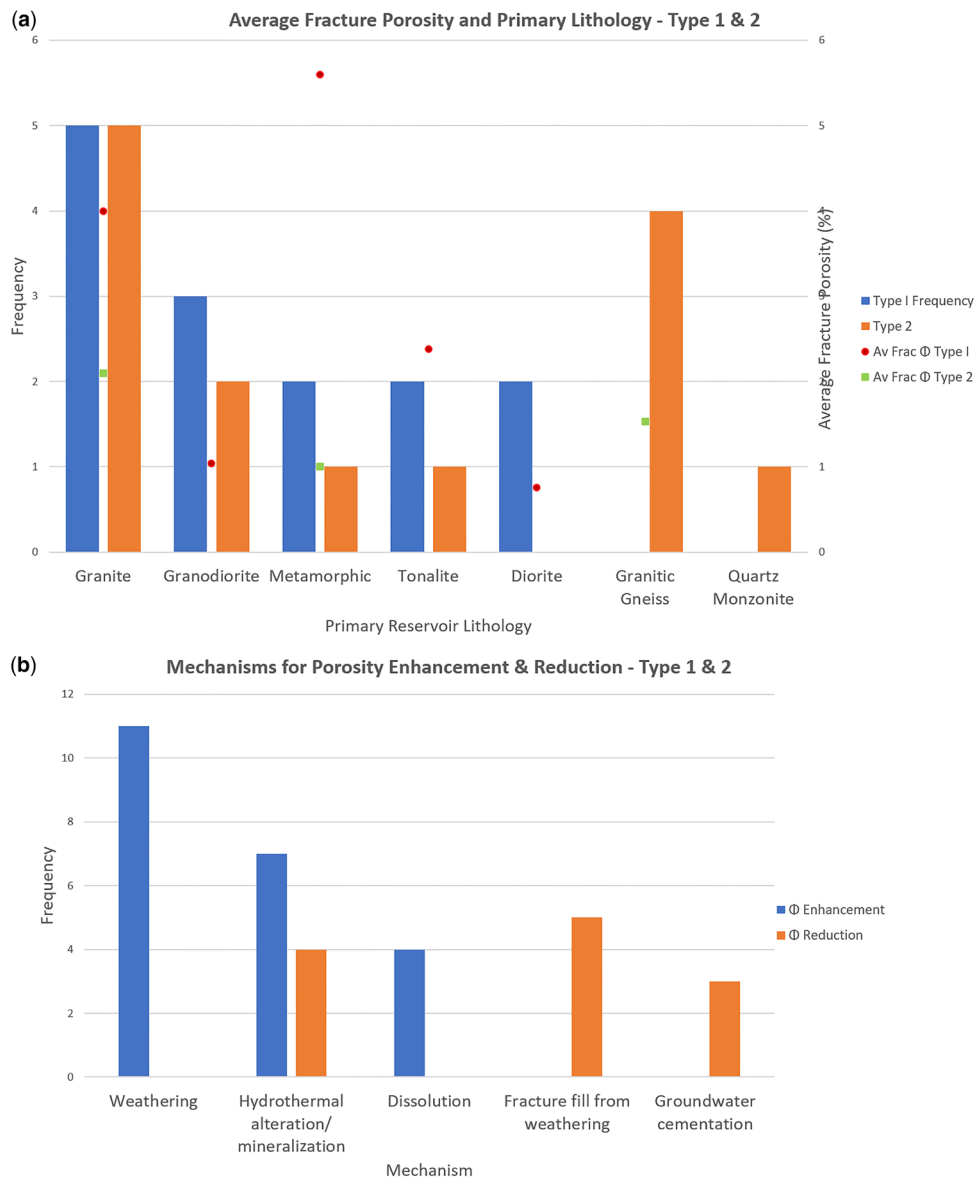


Fig. 11. Average fracture porosities for producing basement fields (a) and mechanisms for porosity enhancement and reduction associated with producing basement fields (b). Source of data DAKS™ (C&C Reservoirs 2018).

and Type II fractured basement reservoirs (Fig. 11b, based on DAKS™). Despite the common occurrence of basement weathering globally, pervasive decametre-scale saprolite development has so far only been reported in the subsurface for the Utsira play. It is therefore postulated that a combination of palaeodrainage associated with a relatively flat palaeotopography (e.g. see Olesen *et al.* 2013) and, perhaps, host-rock mineralogy/texture are the

prime influences on the Utsira saprolite generation. In the absence of clear evidence for differences in palaeo-environment for the four basement plays, the absence of saprolite development at Rona could be a result of the host-rock's metamorphic fabric or the narrow ridge-like form of the basement high. In the latter scenario, it is possible that the palaeohigh was more prone to the effects of marine or subaerial erosion. Thus, saprolite development may have

occurred, but the altered material was continually washed away or down into the fissure systems.

In summary, the Rona, Utsira, Frøya and Lofoten plays show similarities in that they are long-lived subconformity structures that persist today as uplifted footwall basement blocks bounded by Mesozoic normal faults. At Rona and Lofoten, the basement rocks are high-grade metamorphosed tonalities–granodiorites, whereas Utsira is Caledonian and predominantly unmetamorphosed granodiorite. The Frøya lithotype is currently ambiguous, but it seems most likely that it too will be Caledonian granite–granodiorite.

For each of the plays, the fracture, or potential fracture, networks have developed from an initially extensive and deeply penetrating joint system, derived from primary cooling of the igneous and/or metamorphic basement rock. These joints have then likely to have been reactivated and enhanced through the development of open tensile fissures in the near-surface most probably associated with Mesozoic rifting and hydrothermal mineralization (Trice *et al.* 2018; Holdsworth *et al.* 2019). Cenozoic extension, tilting and uplift have potentially further increased the hydrodynamic potential of the fracture networks through tensile failure and fluid flow with dissolution and/or corrosion of minerals. The development of tensile fractures, as opposed to shear fractures, is particularly important in the development of fractured reservoirs. This is because tensile fractures have much bigger apertures, and are likely to be very long and continuous features as they form as unstable Mode I propagating fractures (Fossen 2010). It is envisaged that repeat tensile failure would significantly enhance fracture aperture and trace length growth, thereby efficiently increasing both fracture network connectivity and transmissivity potential. Prior to burial, and perhaps at the same time as active fissuring processes, extensive subaerial exposure provided the potential for unconformity-generated porosity and permeability enhancement through dissolution which can ultimately lead (locally) to the total replacement of the host crystalline rock with saprolite. The latter process was pervasive at Utsira, and possibly also at Frøya and Lofoten.

Effective porosity and permeability development

Achieving an optimal exploration and development strategy for Type I and Type II fractured reservoirs requires an understanding and effective assessment of the fracture network and reservoir fluid distribution (Nelson 2001). Type I fractured reservoirs owe their productivity and storage capacity entirely to a hydrodynamic, or hydraulically conductive, fracture network (National Research Council 1996). The

hydrodynamic fracture network is a subset of the natural fracture network, consisting of fractures that are spatially connected and collectively capable of transmitting fluid (Trice 2014). Fluid flow in the hydrodynamic network is controlled by: (a) fracture connectivity; (b) the relative magnitude of fluid pressure and lithostatic pressure; and (c) the magnitude and orientation of the mean stress across the fracture network (Jolly & Cosgrove 2003). Type II fractured reservoirs have the additional complication of having a matrix component. This matrix component has to be evaluated in relation to its porosity–permeability and fluid saturation, in addition to fracture storage and permeability. Once the static characteristics of the matrix and the fracture components are defined, the modelling of how fluid moves from the matrix to the fracture network becomes the remaining challenge. This basic difference between Type I and Type II reservoirs has a material ‘knock-on’ effect when considering data acquisition and development strategies (Nelson 2001; Allan & Sun 2003).

Despite the currently limited available data for the four plays, significant differences emerge for the known porosity distributions. In the case of the Rona play, porosity is almost entirely associated with fissure fills, joints and microfractures that are present within and without zones associated with larger faults identified from seismic interpretation (Belaïdi *et al.* 2016). This distribution is summarized in Figure 12, which depicts two facies: ‘fault zones’ and ‘fractured basement’. As an example, the average porosity for the Lancaster Field is 4%, with an average fault zone porosity of 4.8% and a fractured basement porosity of 3.2%. Despite the improved porosity associated with fault zones, mapping of porosity using seismic methods is not possible, and areas of potential high porosity are quantified through the mapping of seismic-scale faults and attributing fault zone widths as statistical ranges. Fault zone widths are estimated from the ranges of fault zones established through drilling and wireline data (Belaïdi *et al.* 2016). Porosity generation is attributed to a pre-existing fracture network that has been enhanced by a combination of fissuring (tensile failure), partial mineralization due to influx of hydrothermal fluids (e.g. Fig. 10e) and deep penetration of surface weathering processes down fissures (Trice *et al.* 2018; Holdsworth *et al.* 2019).

In contrast, porosity on the Utsira High has been significantly enhanced through weathering, resulting in saprolite and leading to average recorded porosities in the oil leg of just below 10%. Faults within the basement of the Utsira are well imaged from beam-migrated 3D seismic volumes (CBM). A combination of the properties of the chalk overburden and the porous weathered basement has resulted in the observation that there is a clear relationship

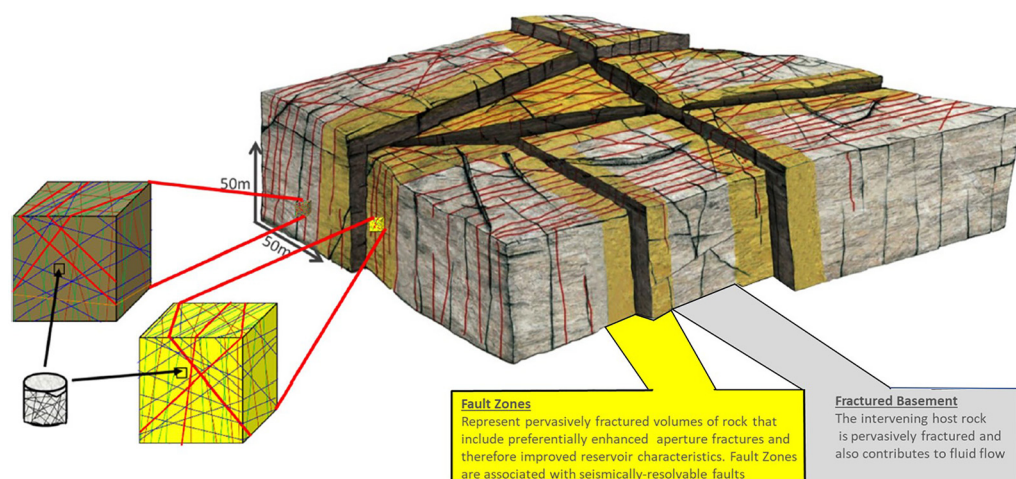


Fig. 12. Conceptual model of the Rona basement play demonstrating a well-connected fracture system comprising microfractures, joints and seismic-scale faults. The reservoirs are divided into two facies: 'fault zones' and 'fractured basement'.

between sonic velocities and degree of fracturing/ weathering in the basement. A combination of geophysical techniques was applied to selecting the 16/1-25s Rolvsnes well, which successfully demonstrated permeable and porous basement consistent with the pre-drill geophysical mapping (Lie *et al.* 2016).

The Rona and Utsira porosities are not atypical of porosity ranges published from Type I and Type II fractured basement fields worldwide (Fig. 9a). However, comparing porosities between fractured basement analogues has severe limits, particularly in Type I reservoirs as it is the fracture network properties and how wells intersect that network that ultimately governs the measured porosity. Given the similar geological histories, it is not unreasonable to suggest that the Frøya and Lofoten plays will have fracture and reservoir properties similar to Utsira and Rona, respectively. It is therefore suggested that the exploration and development methods applied to the Rona and Utsira plays should be considered as a template for the exploration and early appraisal of Frøya and Lofoten. Once a material hydrocarbon presence has been identified from exploration drilling, it is suggested that high-angle wells, with associated drill stem testing, should be drilled to target seismically resolvable faults and orientated perpendicular to regional joint trends.

Current issues with basement play development and knowledge sharing

The proven Rona and Utsira basement plays have thus far been evaluated somewhat differently.

The southern Rona Ridge play (Lancaster and associated prospects) is a stand-alone reservoir with no available local infrastructure, and was therefore explored and appraised with this economic constraint. The Utsira play and the Clair Ridge basement benefit from an overlying reservoir and proximal production facilities. A further material difference is that the oil column at Rolvsnes on the Utsira is confined to 30–40 m (Gaffney Cline 2018). At Lancaster, the oil column is at least 600 m and early production wells therefore require relatively little tolerance in maintaining horizontal well paths in order to avoid encountering the aquifer. At Clair, an oil column of at least 200 m has been encountered in the basement; although so far any potential basement development has been overshadowed by the development of the primary reservoir target in the Devonian–Carboniferous Clair Group sandstones. Drilling at Lancaster is based on accommodating drilling losses as they occur, whereas at Utsira drilling has focused on minimizing drilling losses to the formation. Operators evaluating the Lancaster Field and Rolvsnes discovery have both deployed well paths that cut seismically mapped faults, and have invested in acquiring high-quality, borehole-derived geological and geophysical datasets.

Industry conferences – as represented by this Special Publication – and the Norwegian FORCE (forum for reservoir characterization, reservoir engineering and exploration technology cooperation) have, and are providing, opportunities for the sharing of experience with basement reservoirs from the UKCS and NCS (FORCE 2018). The following subsections provide a summary of some of the current issues being discussed when considering the

fractured basement play and, whilst far from exhaustive, are provided as potential subjects for further cross-border knowledge sharing and/or future conference topics.

The importance of applying a consistent terminology

The terminologies used in describing basement reservoirs are currently varied and potentially confusing. This makes the process of direct comparisons more challenging than necessary. For example, porosity is rarely defined as a specific type (e.g. total, effective, fracture, bulk). Similarly, the methods of porosity derivation/ranges are commonly not recorded. This makes comparisons of porosity attributed solely to a specific fracture type, or through a specific method of derivation, a challenge. Similarly, the term 'fracture' is often used as a bucket term for joints, shear joints and microfractures, and once again this makes direct comparisons between basement reservoirs more difficult than necessary. There are sufficient similarities in the geological characteristics and formation evaluation methods in the four plays described herein to suggest that the defining and application of a generic basement play terminology should be relatively straightforward. Agreeing such a working terminology would be key step in making cross-border knowledge sharing more transparent and effective.

Seismic imaging experience

Since the introduction of broadband seismic acquisition, processing and reprocessing, the interpretation of previous basement highs and platform areas have changed significantly (Patrino & Reid 2017). A common denominator is that the geology becomes more complex and shows greater variability laterally with improved imaging. This is illustrated by the Frøya High, where new and reprocessed seismic data reveal increased levels of detail in the geology and, as a result, a refined more local, structural evolution can be recognized (Fig. 7a, b).

Where saprolite is developed, depth imaging of basement can be difficult without reliable sonic data to guide the velocity model. Lundin have successfully applied a combination of pre-stack Kirchhoff depth migration (KPSDM), controlled beam migration (CBM) and full waveform inversion (FWI), and have utilized refraction data in the velocity model building to image the basement on the Utsira High (Lie *et al.* 2016). Similar methods are now being applied on the Frøya High, including the use of the Common Reflection Angle Migration (CRAM) method. It has proved useful to apply several different processing sequences to provide a

range of seismic volumes for interpretation, seeing that very limited well velocity information exist (Koren & Ravve 2011).

Effective velocity modelling and associated depth migration have not proven to be a significant challenge at the Rona play, but velocity modelling has benefited from vertical seismic profile (VSP) acquisition. In addition, walkaway VSP (Knight *et al.* 2013) has been applied with some success in improving fault imaging (Knight *et al.* 2013). A time and depth reprocessing of 3D seismic data over the Lancaster, Lincoln, Warwick and Whirlwind assets is currently being undertaken, with a view to carrying out specialist reprocessing workflows to improve fault/fracture imaging. Sharing of knowledge and workflows across different basement highs and continental shelves will make seismic processing and reprocessing more effective, and aid in the optimal imaging of structural complexity, as well as the mapping of faults and fractures for optimal well placement.

The drilling process

Both the Utsira and Rona plays have utilized inclined and horizontal well paths. At Utsira, accurate horizontal well paths in excess of 2 km in length have been achieved, whereas at the Lancaster two 1 km horizontal wells have been attempted; in both cases, maintaining the horizontal path has been a challenge. It is probable that the Utsira drilling benefited from the arenaceous nature of the sapropelic reservoir, whereas the highly fractured nature of the Rona basement provided the drilling challenge with frequent bit drops. Whether the differences in drilling experience are completely a function of reservoir properties is uncertain at this time. The impact of applied drilling technology and methods to basement reservoirs is an important topic for future discussion.

One of the most significant drilling challenges in evaluating a basement play arises due to drilling fluid invasion into the formation. This effect is exacerbated by the degree of overbalance, particularly in Type I reservoirs. The net effects of fluid invasion are: (a) potential total losses; (b) formation damage; and (c) deep invasion that has to be accommodated during formation evaluation (Bonter *et al.* 2018). One potential solution to this challenge is by managing overbalance through utilizing controlled mud level methods (CML). Although this technique has been deployed in the NCS, its suitability to fractured basement has not been demonstrated and, to date, CML has yet to be applied to the UK basement reservoirs.

Damage can also be greatly exacerbated by drilling fluid chemistry. Rona has been drilled with

calcium chloride, sodium chloride and calcium bromide brines, as well as mixed metal-oxide muds. Each mud was chosen for a specific operational objective, but experience has taught that the specific properties of the basement lithology when combined with particular drilling fluids can have negative impacts on formation damage, well abandonment operations and wellbore clean-up. One of the most significant examples came from the Halifax well on the Rona Ridge, where the calcium-brine mud interacted with cutting fines to generate a 'slurry' (Fig. 13). Further to chemical and particulate analysis, the slurry is interpreted as likely to have an adverse effect on formation permeability, hole cleaning and drill stem testing. It is expected that the range of lithologies and clay types so far documented across the four plays will be associated with variable responses to different drilling fluids and the degree of overbalance.

Hydrocarbon detection in reservoirs associated with the four plays is possible via gas chromatography and high-resolution gas chromatography techniques (Belaïdi *et al.* 2016; Bonter *et al.* 2018). The relatively low porosity of Type I reservoirs and the associated degree of drilling fluid invasion provides an additional challenge in the detection of hydrocarbon as, compared to typical North Sea clastic reservoirs, the volumes of total gas are relatively low. Moreover, visible oil shows over basement reservoir intervals can be infrequent or absent. A consequence of this is that hydrocarbon-detection strategies have focused on using gas ratio and IsoTube® analysis, and this has proven to be a practical solution to hydrocarbon detection. Knowledge sharing on the subjects of drilling fluids and their application, and mud-logging techniques (particularly gas evaluation and managing overbalance) has the potential to not only impact on optimizing exploration drilling success, but also aid in early appraisal drilling results by reducing formation damage and thereby improving well productivity

Formation evaluation

There are obvious opportunities for knowledge sharing with regard to core and sidewall-core acquisition methods, optimal methods of acquiring wireline pressure, and techniques for isolating specific fracture intervals during drill stem testing. As an example of improvements in formation evaluation, sidewall-core acquisition and analysis from Lancaster and Whirlwind have significantly improved since 2011, with recoveries of up to 95% being achieved. This result has been made possible through a combination of revising operational quality control (QC) and well-site interpretation methods. Furthermore, sidewall-core handling techniques have also been improved, so that previously missed information

on hydrocarbon presence and mobility are now routinely recorded. Linked to the improved sidewall-core acquisition is the use of nuclear magnetic resonance (NMR) acquisition. Since its first application in 2011, this technique is now sufficiently progressed to a level where it is considered a reliable method for effective porosity evaluation and there is a growing body of data to indicate that NMR is also able to detect the presence of hydrocarbon within Type I fractured basement, at least in the Rona play (Bonter *et al.* 2018). Other wireline techniques that have had variable success include spectral gamma, sonic waveform and wireline pressure measurements. Of these, pressure measurements have been successfully acquired at Rona and Utsira using both DST and wireline methods. At Utsira, interval isolation techniques during DST have been successfully applied, but so far this approach has not been attempted in the Rona play. One of the most significant challenges in formation evaluation is the acquisition of wireline pressure measurements where individual fractures are isolated with dual packers. Whilst it is possible to locate prospective fractures for pressure testing, the acquisition of reliable pressures has only been achieved in the Rona basement where wireline pressures have been acquired post-DST testing. In such instances, the negative impact of deep drilling fluid invasion is mitigated by hole cleaning and the subsequent return of the reservoir fluid to the near-bore environment.

From the foregoing discussion, it is obvious that the collation of cross-border information and experience on the above-mentioned formation evaluation techniques could help to establish an optimum borehole design and formation acquisition strategy for both exploration and appraisal programmes of basement plays.

Use of outcrop analogues

Operators have demonstrated the value of outcrop studies in constraining the properties of the Rona and Utsira plays (Slightam 2012; Gunterberg 2013; Pless *et al.* 2015; Lie *et al.* 2016). This trend continues as recent insights into the West of Shetland basement reservoirs (e.g. Holdsworth *et al.* 2018, 2019; Trice *et al.* 2018) have provided evidence of common geological process being shared by the Clair Ridge and south Rona basement. Of particular relevance here is the use of outcrop fault and fracture statistics to constrain fracture frequency and fracture aperture distributions (e.g. Pless 2012; Franklin 2013; Pless *et al.* 2015). Comparing such outcrop information with subsurface data gives confidence in fracture properties and yields important insights into the geological processes that result in subsurface fracture distribution. Exploration strategies have,

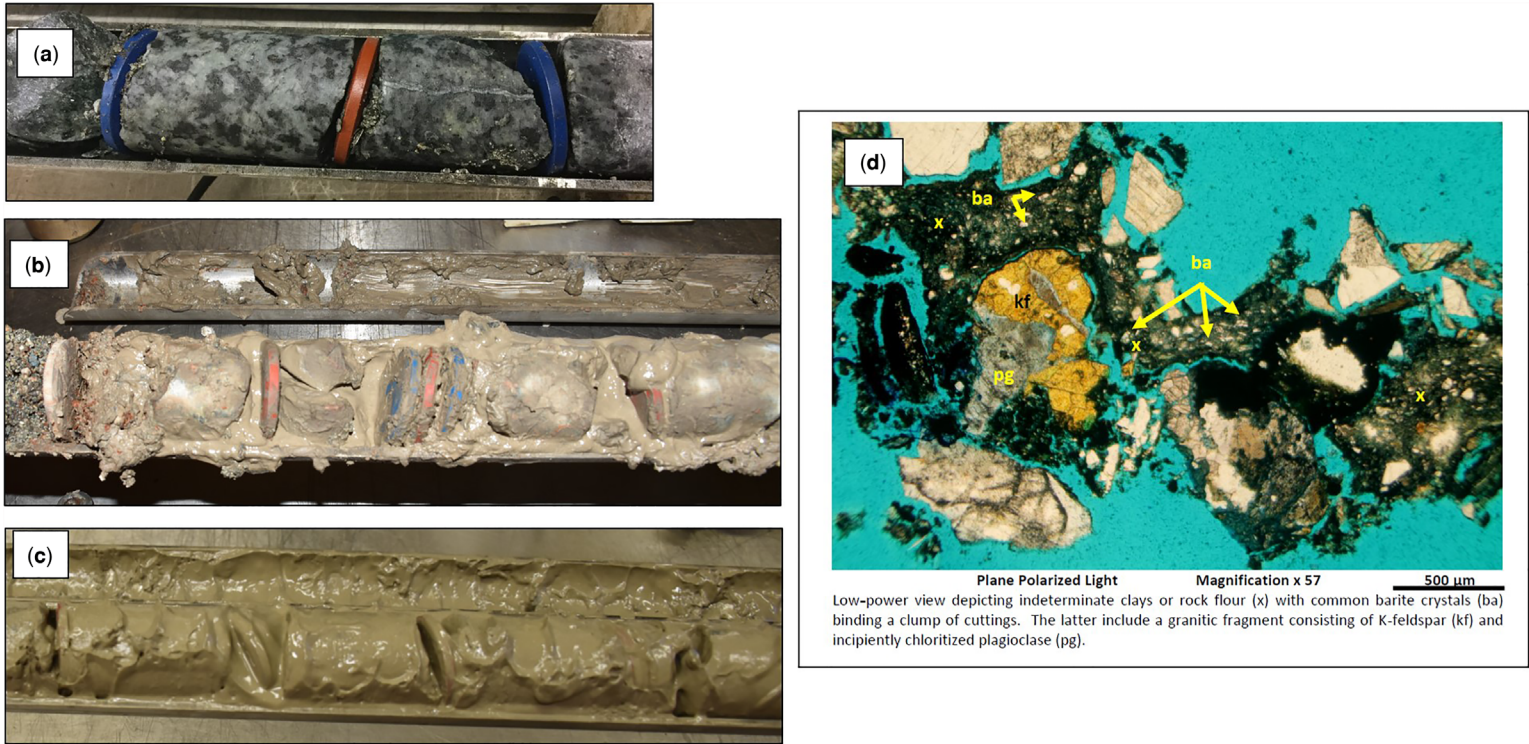


Fig. 13. Opened 1.5 inch-diameter sidewall core barrel (a) portraying typical tonalite sidewall-core recovery. Inserts (b) & (c) demonstrate examples where the sidewall core is association with a glutinous paste comprising drilling fines and drilling brine. Thin-section of the paste (d) portraying its clay grade and binding nature to basement cuttings.

and can, benefit from the use of outcrop analogues. The Lancaster basement exploration well was planned by using outcrop data in the Outer Hebrides to help to constrain anticipated fault widths and connectivity. Post-drilling, the outcrop data were utilized to constrain seismic fault imaging (Slightam 2012). In the case of the Utsira play, fieldwork has materially impacted the industry understanding of the potential for saprolite development and controls of its distribution, as well as how reservoir properties can be enhanced/occluded by weathering. The Bømlø outcrops were also used to constrain the structural deformation history (Scheiber & Viola 2018). Similarly, onshore analogues are also extensively used to try to understand the geological history of the Frøya play. However, due to the limited number of wells and, consequently, the limited knowledge about the types of basement present and the age of the potential Paleozoic basins in the southern part, there is uncertainty related to which onshore areas would be the most suitable analogue(s).

Summary

Most basement penetrations across the UK Continental Shelf (UKCS) and the Norwegian Continental Shelf (NCS) are serendipitous, having been drilled primarily to evaluate shallower exploration targets rather than basement prospectivity. Exceptions to this include the Lancaster and associated discoveries on the Rona Ridge (UK) and Utsira High (Norway), where active exploration and appraisal of basement has led to the sanction of basement reservoir developments.

The collective advances in knowledge that have occurred in the understanding of basement plays provide a growing analogue database and a window of opportunity for increased levels of cross-border knowledge sharing. A number of opportunities now present themselves:

- Sharing of geological understanding of various basement plays, seismic mapping and processing techniques, and the integration of well data into effective prediction of fault and fracture networks in the subsurface.
- Observed differences in reservoir properties associated with the degree and style of basement weathering as seen for the Utsira and Rona plays provide end-member models for considering well placement and data acquisition strategies in undrilled UKCS–NCS basement plays.
- Optimized basement drilling techniques and well completion designs should be shared through a collaborative review of lessons learnt.
- Continued improvement regarding approaches to formation evaluation and data acquisition to

effectively address the potential risks and opportunities that need to be considered in planning exploration and appraisal well programmes.

- Standardizing the use of basement play-related terminology will ensure effective and meaningful knowledge transfer.
- Improved understanding of key processes such as fault, fracture, joint and fissure formation during active rifting, near-surface hydrothermal mineralization, dissolution and weathering processes is required in the geological community in general.
- Sharing of best practices in utilizing outcrop analogues to better predict subsurface fracture attributes, the impact on reservoir properties from weathering processes and how basement reservoir fracture networks impact fluid transport in the subsurface.

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